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Towards Automotive NVH Enhancement: Structural Dynamics Analysis of a Vehicle Wheel

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Abstract

The pneumatic tire is a key component of a vehicle since it transmits vibrations and disturbance from a typical road to the vehicle body structure. It is important to analyze dynamics of a tire to control the NVH (Noise, Vibration and harshness) level of a whole vehicle body structure. In this paper, a finite element of a whole wheel (including a rim and a tire) has been developed and a through dynamic analysis is done to find the resonance frequencies and corresponding mode shapes. These resonance frequencies and mode shapes can be used as the input parameters for BIW (Body-In-White) design in early design phases. It can significantly enhance dynamical performance of a vehicle body structure and at the same time reduce the manufacturing cost and time. Because a reliable and precise dynamic model of the tire gives the opportunity to have an optimized design in geometries and materials, here, we have developed a finite element (FE) model for the wheel and a comprehensive dynamic analysis is conducted.

Keywords: NVH optimization; Automotive Wheel FE Analysis; Resonance Frequencies; Mode Shapes.

1. Introduction

There are a lot of complaints from passengers about discomfort due to vehicle body vibrations and the generated noise inside the cabin [1]. The noise and vibration of a vehicle body can be controlled and tuned in early phases thanks to the advancement in CAE (Computer Aided Engineering) technology [2,3].

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The CAE methodology provides a facile, low cost and unique tool to have a better understanding of the dynamic behavior (Resonance Frequencies, mode shapes, Frequency Response Functions, Mode shape interaction) of the automotive body structure.[4-6] Noise and vibrations from the road or automotive engine directly transfer to the passenger through the seat structure. Seat structural dynamics has been analyzed [2] as it is considered as an important source of BSR noise which can be annoying for a typical passenger for a regular ride [7,8].

Tires as the primary contact of an automotive to the road plays an important role to transfer the road disturbances to the BIW [9-11]. Automotive tires have a complicated structure consisting of so many materials which can make it difficult for stress and strain analysis. The reason is that all the connections and spot welds have to be modeled correctly to have reliable results. But, from structural dynamics point of view, simpler models can be employed to investigate dynamics of the whole wheel. Concept modeling method for the whole automotive body structure has been previously discussed [12]. Previous studies show that, in general, tires have two modes of vibrations: (1) in low frequencies (10 Hz to 20 Hz) it vibrates like a uniform object (mass-spring system and [13] (2) in high frequencies (250 Hz to 500 Hz), dynamical behavior is nonlinear and it would be complicated since it is considered as a distributed system [14]. It has been shown that for frequencies less than 500 Hz, the whole wheel structure (not all the parts separately) has a modal and linear dynamical behavior [14]. Therefore, it is possible to develop a simple finite element model which is useful for vibration analysis and also does not include the detailed parts like connections [12]. In this paper, a FE model of the tire and rim has been developed using Hyperworks software. A through dynamic analysis also has been conducted to extract resonance frequencies and also mode shapes of the system.

2. Finite Element (FE) Model of the Rim

Dynamical reaction between rim and the tire is important in an automotive NVH performance analysis. Tires damping also need to be modeled and considered since it is a hyperelastic material [15]. It has been shown that in the frequency range between 200 and 350 Hz, there is 5 dB difference in interior noise level for aluminum and steel rims [16]. In general, the first resonance frequency of the steel rims is 100 Hz smaller than that of aluminum ones [17]. Figure 1 shows finite element model of the ring made of steel material with diameter of 30 mm. The weight of the ring structure is 6.159 kg, and also structural damping is 0.01. This model is made with shell elements and has 3 main parts with characteristics listed in Table 1.

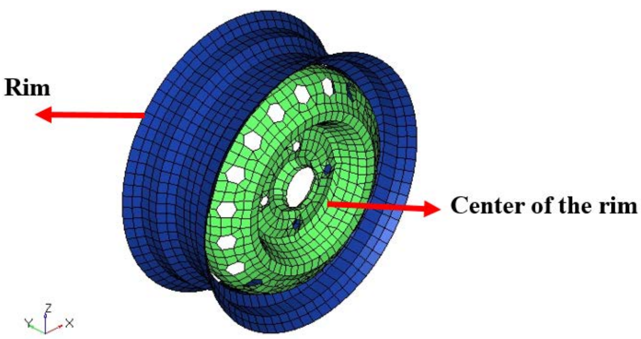

Figure 1: FE model of the whole rim.

Table 1: Properties of different components in FE modeling of the rim.

Model Properties	Rim	Center of the wheel	Elements of spot weld
Material	Steel	Steel	Steel
Young’s modulus (GPa)	210	210	210
Poison’s ratio	0.3	0.3	0.3
Density (kg/m3)	7900	7900	7900
Wight (kg)	3.27	2.81	0.08
Damping	0.01	0.01	0.01
Element name	PShell	PShell	PShell
Element type	2D	2D	2D
Thickness of the element (mm)	2.5	3.5	5

Another important part in FE modeling of the rim is the connection between center of the rim and the rim. These two parts are attached through welding from four areas with a length of 8 cm. Here RBE2 elements have been used to attach these parts (Figure 2)

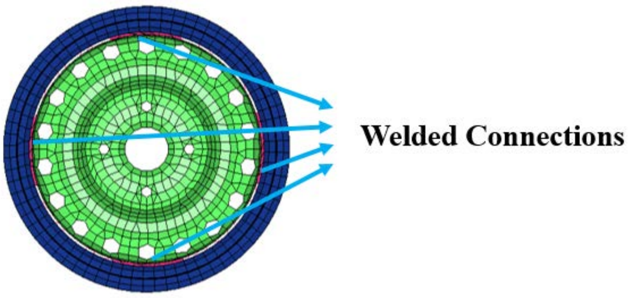

Figure 2: Welded connections to bond the rim and the center of the rim

3. Finite Element (FE) Model of the Tire

3.1. Theory of the tire models

Tires as incompressible materials can be molded with hyperelastic properties [18]. Hyperelastic materials can have 500% to 1000% strain without failure. Neo Hookean model can be used when the strain of the material is small (less than 30 %), and the strain energy density function for an incompressible neo-Hookean material is:

$$W = C_1(I_1 - 3) \qquad (1)$$

Where C_1 is a material constant, and I_1 is the first invariant of the right Cauchy-Green deformation tensor.

3.2. Finite element model of the tire

Figure 3 shows finite element of the tire and its cross section in Hyperworks software. 3D solid elements are used to create the model. Table 2 shows the material properties and element types of the tire.

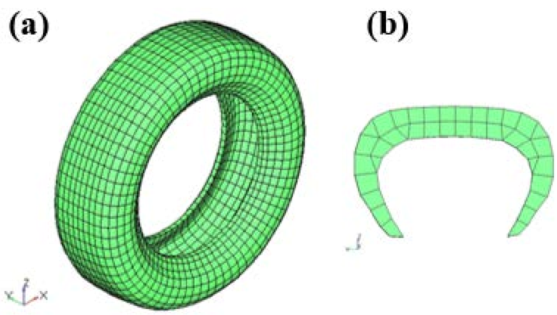

Figure 3: FE model of the tire and its cross section.

Table 2: Material Properties and element types used to model the tire.

Young's modulus (MPa)	320
Damping coefficient	0.15
Poison's ratio	0.45
Density (kg/m3)	650
Wight (kg)	6.14
Element name	PSolid
Element type	3D

4. Finite Element (FE) Model of the Entire Wheel

Figure 4 shows FE model of the entire wheel including the rim and the tire. In order to bond the rim and the tire, RBE elements is employed. The weight of the whole structure is 12.34 kg.

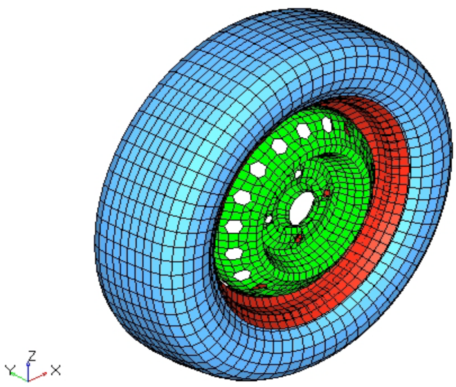

Figure 4: FE model of the wheel structure.

5. Results

In order to dynamically analyze the behavior of the wheel structure, its mode shapes and resonance frequencies have been computed and derived respectively. Resonance frequencies of the rim is listed in Table 3 starting from 250 Hz to 1370 Hz.

Table 3: Mode shape and resonance frequencies of the rim.

Mode Number	Mode Type	Frequency (Hz)
7^{th} mode	Bending mode	245
8^{th} mode	Torsion mode	257
9^{th} mode	First triangle mode	685
10^{th} mode	Second triangle mode	693
11^{th} mode	First rectangular mode	1152
12^{th} mode	Second rectangular mode	1178
13^{th} mode	Axial mode	1370

Figure 5 demonstrates the mode shapes of the rim corresponding to the resonance frequencies. Mode shapes include different modes of movement such as bending, torsional and their combinations along with higher order modes. As we expected, for higher frequencies, corresponding mode shapes are getting complicated shapes. But, our focus in NVH optimization is on the frequencies less than 500 Hz.

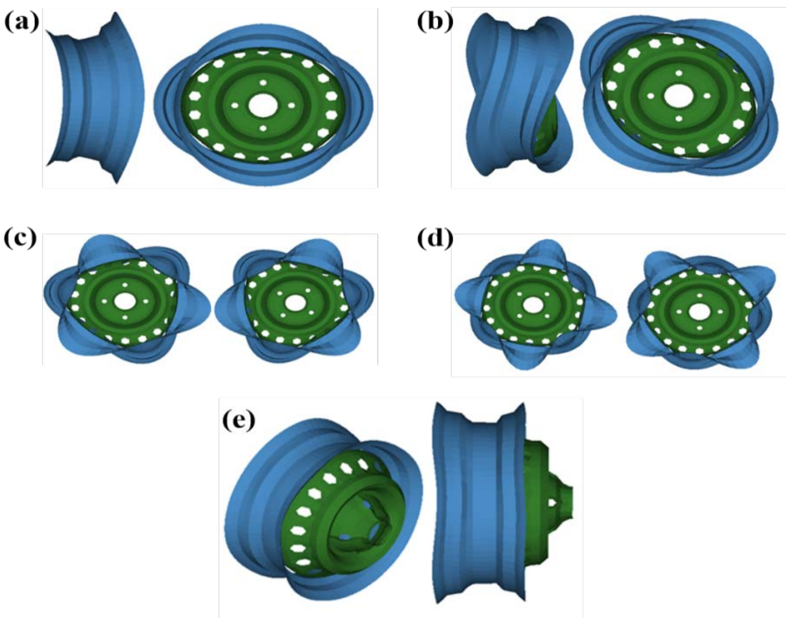

Figure 5: Mode shapes of the rim: a) bending mode b) twisting mode c) 3^{rd} and 4^{th} modes d) 5^{th} and 6^{th} modes e) appearing of local modes

Table 4: Mode shapes and resonance frequencies for the hyperelastic tire.

Mode Number	Shape of the mode	Resonance frequency (Hz)
7^{th} mode	Elliptic	35
8^{th} mode	Triangle	70
9^{th} mode	Rectangluar	88

Table 4 shows the resonance frequency values of the tire from 35 to 88 Hz and corresponding mode shapes is also illustrated in Figure 6.

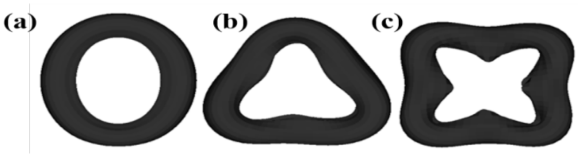

Figure 6: 7^{th} to 9^{th} mode shapes of the tire (Higher frequencies have complicated mode shapes)

Finally, the whole wheel composed of tire and the rim is analyzed to derive the resonance frequencies and mode shapes. Resonance frequencies of the wheel are tabled in Table 5. You can see that all resonance frequencies are below 200 Hz. These resonance frequencies when combined with low frequency disturbance of noise sources (road and engine) have to be studied in early design phases of the automotive body. Figure 7 demonstrates mode shapes of the wheel corresponding to resonance frequencies.

Table 5: Mode shapes and resonance frequencies of the modeled wheel.

Mode number	Shape of the mode	Resonance Frequency (Hz)
7^{th} mode	Axial mode	68
8^{th} mode	Twisting mode	93
9^{th} mode	Elliptical mode	124
10^{th} mode	Triangular mode	152
11^{th} mode	Rectangular mode	190

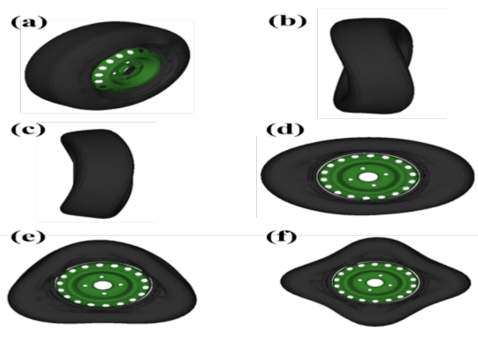

Figure 7: Mode shapes of the wheel: a) axial mode, b) twisting mode, c) bending mode d) elliptical mode, e&f) higher order modes

6. Conclusion

In conclusion, the pneumatic tire forms a vital component of a road vehicle as it interacts with the road to produce the forces necessary for support and movement of the vehicle. Tire as one of the most important components of vehicles requires fulfilling a fundamental set of functions such as: provide load-carrying capacity, cushioning and dampening, stability, reducing noise and vibration, transmit driving and braking torque, resist abrasion, generate steering response, have low rolling resistance, durability throughout the expected life span. Therefore NVH performance of the wheel (including tire and rim) is important to be analyzed. Here, as the first step, a finite element model of the wheel has been derived using Hyperworks software. Then, dynamic analysis of the structure is conducted to derive mode shapes and resonance frequencies. These resonance frequencies and mode shapes can be used in early design phase of the automotive body, since when they are coupled with resonance frequencies of the automotive body structure, interior noise level can be magnified.

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